Major Groundwater Reservoirs of Egypt

Mohamed H. Geriesh, Abdou Abouelmagd, and Basma M. H. Mansour

Abstract

Egypt is known as the Nile's gift because it relies on the Nile River for around 94% of its freshwater resources. As a result, Egypt's national security is clearly dependent on the Nile River, where over a hundred million people are now concentrated in a narrow swath of the Nile Valley, which stretches from Aswan in the south to Cairo in the north. The Nile Valley and Delta are home to more than 97% of Egypt's population. The Nile River supplies Egypt with 55.5 billion m^3/year reflecting that the average available fresh water resources stand at 600 m^3/year/capita in 2020 but considering population growth is expected to drop below the 500 m^3/year/capita threshold of absolute water scarcity by 2030. The strategy of the Egyptian Government indicates that the agriculture sector holds 85%, industry 9.5%, and drinking 5.5%. Egypt anticipates a severe water shortage because of the Grand Ethiopian Renaissance Dam (GERD) building upstream of the Blue Nile. Great water demands due to increasing population rate and fixing water resource budget along with great water losses due to evaporation damming of water flow and supply are expected. Therefore, a promising strategic plan to develop water resources in Egypt that depends on developing traditional and non-traditional water resource supplies is recommended. Additionally, the deep groundwater beneath the vast deserts of the western, eastern, and Sinai Peninsula along with limited quantities of rainwater and flooding are considered non-renewable resources and can be exploited according to the development conditions and the water needs. Non-traditional water resources include the reuse of exhaust uses from agriculture, industry, sanitary, industrial sewage, and desalination. This chapter sheds the light on Egypt's major groundwater reservoirs as a potential and strategic solution for water shortage for expanding agricultural and economic activities until 2030. Egypt's primary groundwater reservoirs are comprised of six aquifers, namely: (1) the aquifers of the Nile Valley and Delta, which are recognized as Egypt's primary source of groundwater supplies and they both provide about 85% of all groundwater abstractions. Annual aquifer withdrawals are estimated at 6.1 Bm^3/year, which is mostly replenished by excess irrigation water infiltration or through the irrigation network and Nile distributaries (2) The Nubian Sandstone Aquifer System (NSAS) is Africa's largest fossil aquifer system, with estimated reserves of 150.000 Bm^3. Around 2.2 million km^2 of the NSAS are shared by Egypt, Libya, Sudan, and Chad, with Egypt contributing 828,000 km^2 (38%). The thickness of the fresh water-bearing layer ranges from 200 meters in East Uwinat to 3,500 meters in the northwestern of El-Farafra Oasis. Between East Uweinat and El-Farafra Oasis, the fresh water layer's thickness ranges from 200 to 3500 m. Recent studies have revealed that the NSAS receives transboundary recharge from Egypt's, Sudan's, and Chad's southern and southwestern borders, as well as local recharge through major fractures and joints along its southern outcrops; (3) the Fissured Carbonate Rock Aquifer, which occupies more than half of Egypt's land area and stretches from the Sinai Peninsula to Libya. . It serves as a confining layer on top of the Nubian Sandstone Aquifer System and features numerous natural springs.; (4) the Fissured Basement Aquifer System, which is located in the Eastern Desert and the southern Sinai Peninsula and is often recharged by modern rainfall ; (5) the Moghra aquifer, which is located in the northwestern Desert of Egypt and the groundwater is flowing towards the Qattara Depression; (6) the Coastal Aquifers that are located along the coastal areas on the Mediterranean and Red seas. The groundwater abstractions are limited due to the risk of saltwater upconing . The groundwater reserve storage in these six aquifers has been estimated to be roughly 1200 Bm^3 with variable recharge

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rates. The long-term sustainability of these aquifers depends on corrective actions including lowering the number of pumping wells, decreasing start-up and operating times, and setting up a drip irrigation system. It is strongly advised to monitor the quantity and quality of groundwater resources.

Keywords

Groundwater reservoirs • Moghra Aquifer • Nile Valley Aquifer • Nile Delta aquifer • Aquifer of Nubian Sandstone Aquifer System • El-Farafra Oasis • Egypt

1 Introduction

Egypt is the Nile's gift (Herodotus, c. 425 BC) as it is dependent on the Nile River in providing approximately 94% of its freshwater resources. As a result, Egypt's national security is clearly dependent on the Nile River, where more than 100 million people are now confined to a small area of the Nile Valley that stretches from Cairo in the north to Aswan in the south. Further, Northern Egypt's Nile Delta population, is quite dependent on the Nile River, whether for drinking, agriculture, industry, or other economic activities. The Nile basin includes a significant mass of Egypt, with the exception of numerous ephemeral drainage networks that drain the Red Sea Hills in the Eastern Desert toward the Red Sea and to the Western Desert in the west. The longest river in the world is the Nile River and the only perennial river that crosses the Sahara Desert, with an estimated length of 6800 km (Said, 1981). The basin course of this significant river is remarkable in that it nearly totally flows from south to north before emptying into the Mediterranean Sea at a latitude of 31° N (Fig. 1). Its basin is relatively narrow and modest in contrast to most other prominent rivers around the world. The Nile Valley and its Delta stretch from south of the Nile valley to the Mediterranean Sea extending from Aswan to the south of Cairo to the Mediterranean Sea north of Cairo. . The Nile Valley and Delta are home to about 97% of Egypt's population (Frenken, 2005). The Nile River supplies Egypt with 55.5 billion m^3/year reflecting that the average available fresh water resources stand at 600 m^3/year/capita in 2020 but considering population growth is expected to drop below the 500 m^3/year/capita threshold of absolute water scarcity by 2030 (FAO, 2016). Further water shortage is expected due to building dams on upstream areas of the Nile River. Significant water losses due to evaporation and damming of water flow and supply are expected, as well as the risk of destructive flooding if such dams have weak structural integrity after its complete filling with water is another scenario (Mohamed & El-Mahdy, 2017). The water losses are usually caused by either poor land-use practices, including the building of canals and drains in poorly suited areas, or flood irrigation techniques (Geriesh et al., 2015; Mansour, 2015). In 1987, the Egyptian government developed a water master plan. This was the first organized attempt to envision the future of the country's water resources and its use. To follow up with that plan, the Ministry of Water Resources and Irrigation (MWRI) established a multidisciplinary group in 2017 to picture the future of water resources and their applicationsT. Egypt's water resources development strategy is based primarily on the development of traditional and non-traditional water resource supplies. It has been common to distinguish between two types of supply:

1. Natural or physical resources: means the volume of water available, whether visible or underground, salty, or fresh.
2. Available resources: The actual available water supply from various water sources is difficult for humans to exploit economically.

According to the Nile Waters Agreement, which Sudan and Egypt signed in 1959 to give themselves full authority over the use of the Nile waters, the Nile River's water resources offer a sizable supply, amounting to 55.5 billion cubic meters annually. Furthermore, deep groundwater beneath enormous deserts in the western, eastern, and Sinai Peninsula, in addition limited amounts of rains and flooding, are considered non-renewable resources that can be utilized based on development conditions and water needs. Non-traditional water resources include the reuse of exhaust uses from agriculture, industry, sanitary, and industrial sewage.

Another unconventional source is the exploitation of shallow underground aquifers in the Nile Delta and valley whose water comes from Nile water leakage or canals, banks, and agricultural water. Finally, desalination as a potential water resource can be exploited, especially on coastal areas on the northern and eastern borders, and some local aquifers with very high-water salinity. The strategy also indicates that the agriculture sector uses 85%, industry 9.5%, and drinking 5.5% of the available water. The water resource development strategy is divided into various stages, the most important of which are:

- Developing additional water resources by expanding the uses of the desalinated saltwater plants to reach 11 billion m^3 and exploitation of the deep groundwater to reach 5 billion m^3.
- Establishing joint projects with countries of the Nile River basin.
- Applying best management practices that maximize water uses to reconcile the different needs of providing drinking, domestic, agriculture, river navigation, and demands for power production.

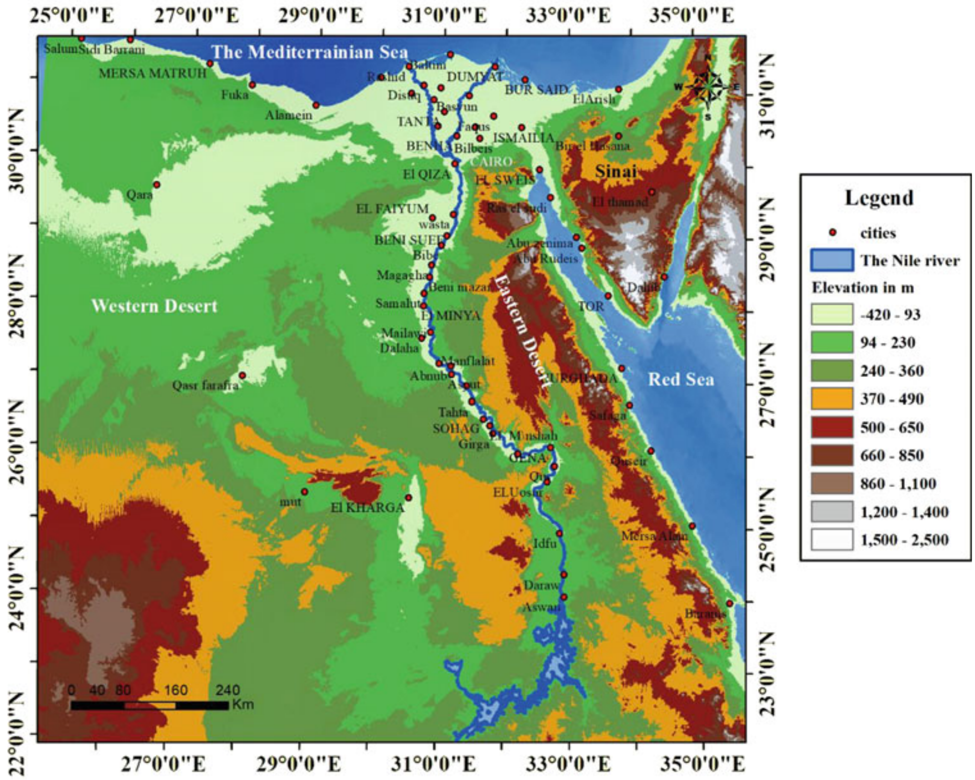

Fig. 1 Nile River location and physiographic map of Egypt

- Maintaining the flow of the Nile River and waterways at a cost of 255 million EGP through the implementation of maintenance and periodic disinfection of irrigation and drainage networks, as well as covering canals and banks that infiltrate residential areas at a cost of 1.4 billion EGP.
- Maintaining a high standard of water quality through cooperation with relevant ministries in the treatment of wastes from industrial and sewage.
- Daily coordination with various ministries and agencies (the ministries of agriculture, electricity, tourism, transport, housing, health, and interior).

This chapter sheds light on Egypt's major groundwater reservoirs (i.e., aquifers) as a potential and strategic solution for water shortage, thus expanding agricultural and economic activities according to the 2030 national plan.

Egypt's primary groundwater reservoirs are made up of six primary aquifers, which are listed below (Fig. 2):

- The Nile Valley and Nile Delta Aquifer (NVNDA).
- The Nubian Sandstone Aquifer System (NSAS).
- The Fissured Carbonate Rock Aquifer (FCRA).
- The Fissured Hard Rock Aquifer (FHRA).
- The Moghra Aquifer.
- The Coastal Aquifer.

2 Nile Valley and Nile Delta Aquifer (NVNDA)

The NVNDA aquifer is of Quaternary and Late Tertiary age, and is overlain by the Nile flood plain, Nile Delta, and its desert fringes. In its majority, it consists of a thick layer of graded sand and gravel that is covered by a clay layer. .

2.1 Geologic and Hydrogeologic Settings

The geologic succession of the Nile Valley ranges in age from Precambrian to Quaternary. Precambrian rocks are mostly igneous and metamorphic in nature. The basement complex's sedimentary strata date from the Paleozoic to the Recent. The NVNDA is mostly made up of Quaternary fluvial sediments. Figure 3 illustrates how its thickness ranges from 300 m in the Middle of Egypt (Sohag Governorate) to just a few meters in the north towards Cairo and south towards Aswan. (Fig. 3). There is no hydraulic linkage between the NVNDA and the underlying Nubian Sandstone Aquifer due to the presence of impermeable Pliocene clayey layers underneath the NVNDA aquifer. However, there could be a linkage between the Quaternary deposits of the

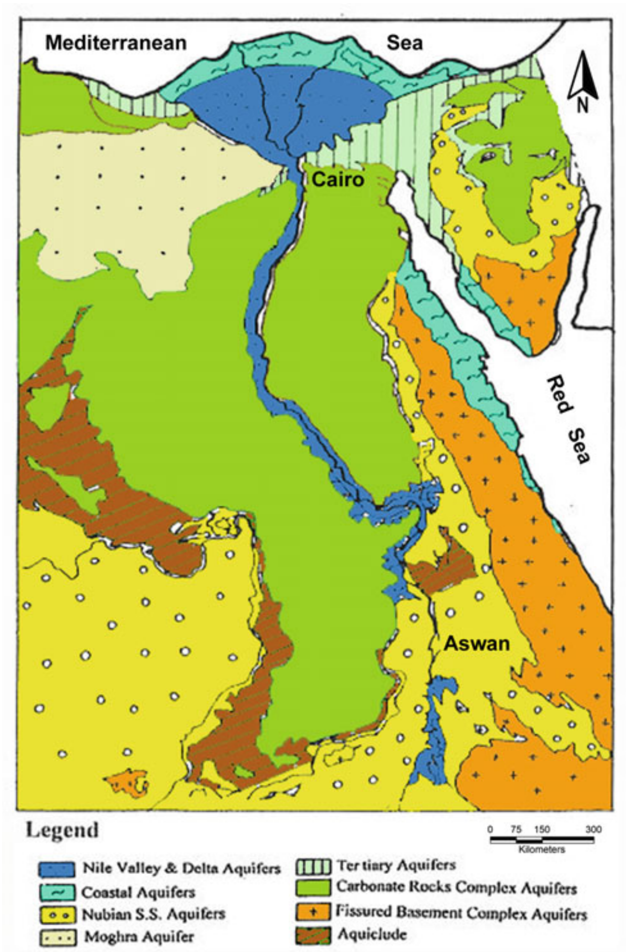

Fig. 2 Hydrogeologic map showing the major groundwater aquifers in Egypt (modified after RIGW/IWACO, 1988)

NVNDA aquifer and the surrounding limestone rocks (Geriesh, 1998). The entire Egyptian Nile Valley is governed by wrench faults that run parallel to both Gulfs of Suez and Aqaba (Geriesh et al., 2020; Youssef, 1968).

Because its salinity is less than 1500 parts per million, the water in the NVNDA is mostly used for domestic uses and irrigation. The NVNDA is a renewable resource, with key recharge sources being infiltration from surplus agricultural water application and leakage from the irrigation canals (El Tahlawi et al., 2008; Geriesh, 1998; Geriesh et al., 2015). The NVNDA's saturated thickness ranges from 10 to 200 m and its hydraulic conductivity, on the other hand, ranges from 50 to 70 m/day. The Fluvial Pleistocene aquifer (*MitGhamr Formation*) is the Nile Delta's principal groundwater-bearing layer. It is mostly composed of gravely sand with interbedded and low-extendable clay lenses in the north. The Nile Delta Aquifer is classified as a semi-confined aquifer because it is overlain by Holocene silt, clay, and fine sand in the Nile floodplain (Fig. 4). In the Delta's northwestern part, a calcareous loamy layer with a thickness varying from 0 to 20 m acts as a confining layer beyond the floodplain. However, there is a hydraulic connection between the Quaternary aquifer and the Moghra aquifer to the west (Fig. 2). Such connection can be confirmed by observing the westward continuation of the piezometric gradient . At the desert's fringes, the semi-confined layer is vanished, and phreatic conditions prevail (El Tahlawi et al., 2008; Geriesh et al., 2015). The thickness of the groundwater storage strata varies depending on location; nevertheless, 190 m is the average thickness. It progressively rises to the north, reaching 350 m in Tanta City. The water layer thickness ranges between 120 and

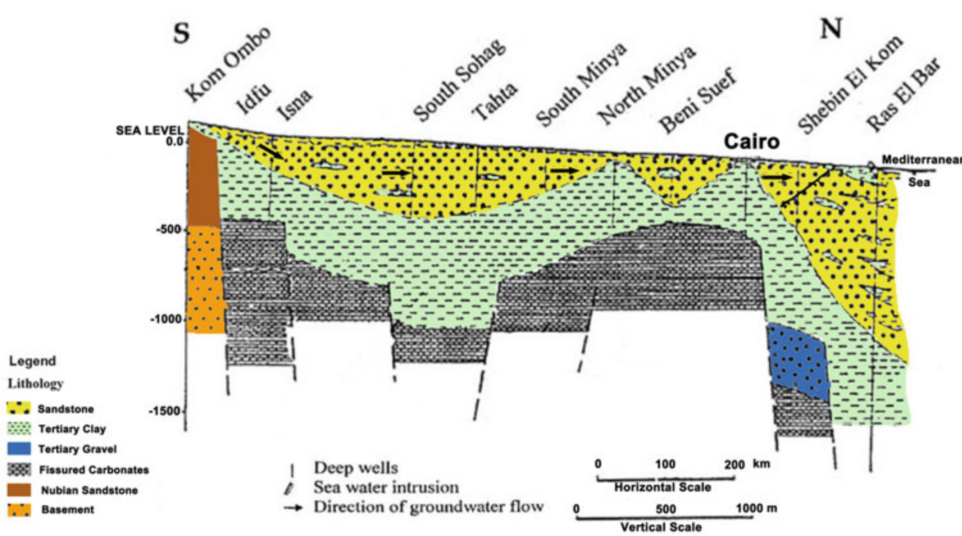

Fig. 3 Hydrogeologic profile through the Nile Valley and Delta basins (modified after Hefny & Shata, 2004)

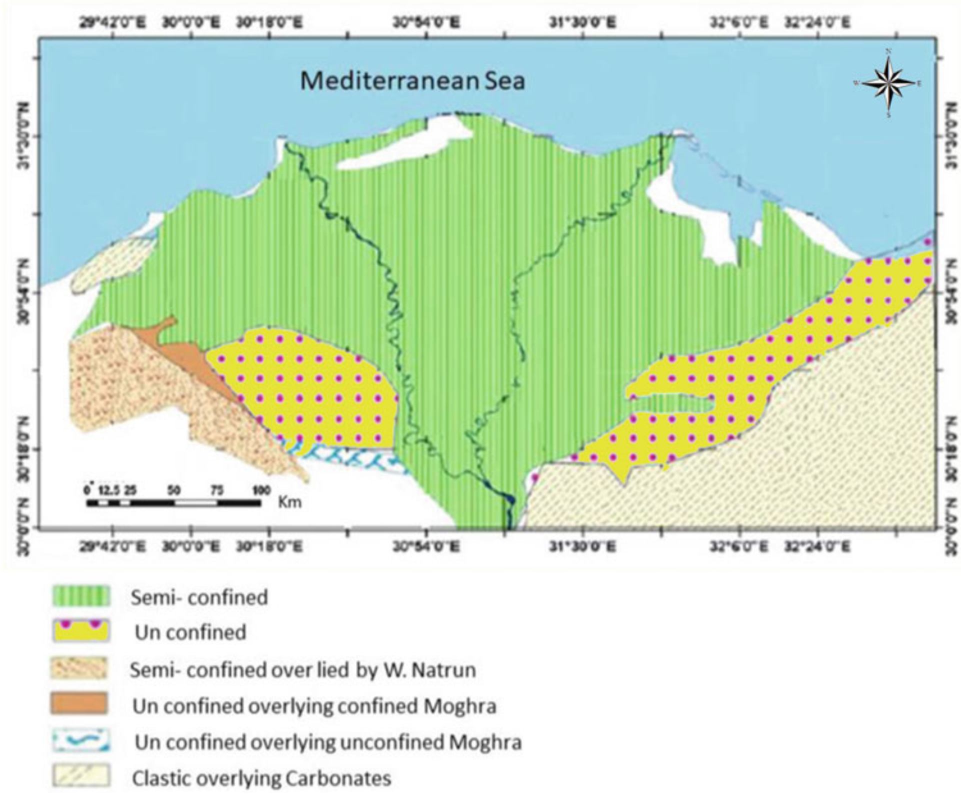

Fig. 4 Groundwater aquifers in the Nile Delta (modified after El Tahlawi et al., 2008)

220 m in the western section of the Nile Delta, and gradually decreasing toward the east. The entire thickness of the aquifer grows from Cairo northward to reach about 1000 m toward the Mediterranean coast (Idris & Nour, 1990). The depth of the groundwater level in the Nile Delta Aquifer increases from north to south. It ranges from one to two meters in the north to three to four meters in the center and five meters in the south (Armanious et al., 1988).

Because the salinity does not exceed 1000 ppm, the southern part of the aquifer has better quality and quantity than the northern part as the irrigation water infiltration always recharges the aquifer (Geriesh et al., 2015; Idris & Nour, 1990). In the Quaternary Nile Delta aquifer, the horizontal hydraulic conductivity ranges between 0.05 and 0.5 m/day. The storage coefficient ranges between 10^{-4} and 10^{-3}, with 0.3 indicating the porosity of the aquifer medium. The transmissivity ranges from 500 m^2/day at the desert's edge to 25,000 m^2/day in the Nile Delta's apex. The northern regions of the aquifer have quite distinct conditions as the aquifer becomes less productive, higher salinity due to saltwater upconing, high evaporation, and rising groundwater levels, Figure 5 depicts the vertical distribution of the water-bearing layers in the Nile Delta 5). The Holocene silty sand and mud (*Belqas Formation*) overlay the Pleistocene aquifer along the main southern flood plain but with an extremely variable thickness ranging from the south to north between 4 and 50 m, respectively. This aquifer is also confined along the northern boundaries, especially along the coastal zone. While the majority of the other parts of the desert fringes are considered unconfined, the Pleistocene aquifer is generally under phreatic conditions. Several perched aquifers are formed together with the northern coastal plain's lowlands and the Delta of Wadi El-Tumilat branched to the east, particularly within dune accumulations. Most of these parts are suffering from water logging and soil salinization due to the high prevailing evaporation rate (El-Fawal & Shendi, 1991; Geriesh, 2000). Global glacial-eustatic sea-level changes were the most powerful paleoenvironmental impacts the Nile Delta's groundwater flow regimes, particularly throughout the Quaternary period (Diab et al., 1997; Fairbanks, 1989; Geirnaert & Laeven, 1992; Geriesh, 2000; Geriesh et al., 2015; Perissorateis & Conispoliatis, 2003; Zaghloul et al., 1979).

2.2 Palaeohydrogeologic History

The Nile Delta's principal fluvial Pleistocene aquifer is the most potential water-bearing layer. It is made of porous sand and gravel with clay lenses and has a maximum thickness of around 975 m (Zaghloul et al., 1979). At the central Nile Delta, the Holocene silt and clays overlay the Pleistocene

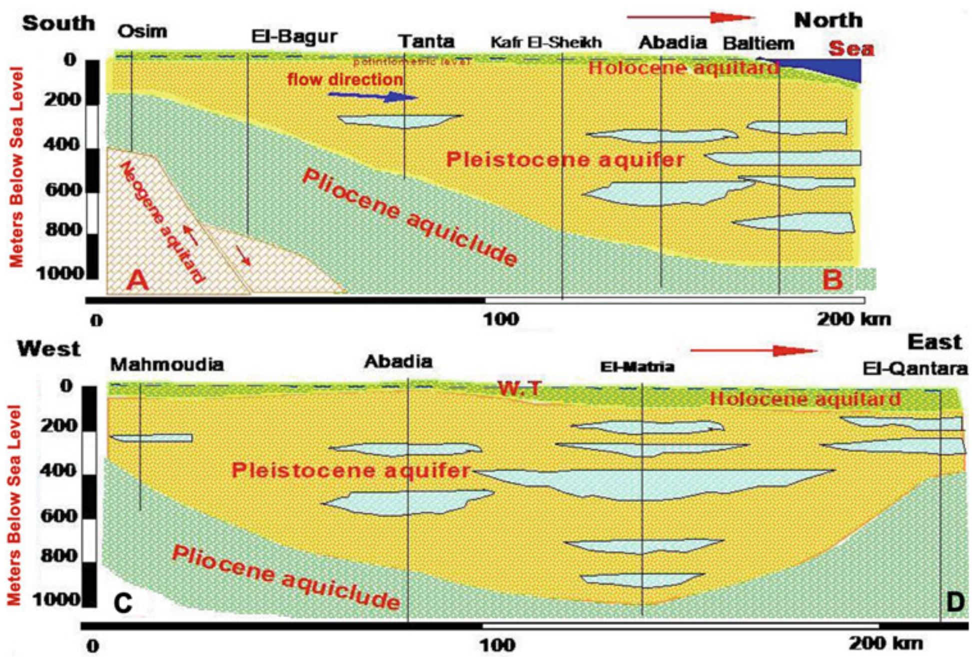

Fig. 5 Hydrogeologic cross-sections in the Nile Delta (modified after Geriesh et al., 2015)

aquifer. While along the western and eastern flanks, it is unconformably overlain by a thin reddish pebbly gravel layer, most probably El Abbassia gravel, which was deposited by the Late Pre Nile-early New Nile system (Said, 1981). In most areas, the Miocene and Pliocene successions underlain the Quaternary sediments in the Nile delta, functioning as an impermeable layer for the main Quaternary aquifers. From bottom to top, the Nile Delta's Neogene-Quaternary subsurface is divided into eight formations: *Sidi Salim, Qawasim, Rosetta, Abu Madi, Kafr El-Sheikh, El-Wastani, Mit Ghamr, and Bilqas*. Three cycles are represented by these formations (Rizzini et al., 1978) or four cycles (Zaghloul et al., 1979) and can be distinguished based on the environmental conditions of deposition (Fig. 3). The Neogene-Quaternary succession is mainly represented by shale , with interbedded layers of dolomitic marl in the bottom section and sandstone and siltstone at the top. According to Zaghloul et al. (1979), the shale has a foreshore to nearly deep marine character and was formed in a transgressive sea, whereas the top sandstone appears to have been deposited in a somewhat regressive sea. The *Mit Ghamr Formation*, on the other hand, is the most important hydrogeological unit in the aforementioned successions. Its thickness increases gradually northwards and is open into the sea to form the Nile cone deposit (Fig. 5). This unit's basin mostly covered the area of the present Delta, and its fringes with a shoreline formed nearly at the present coast but extended further southeast and southwest (Attia, 1954). The Pleistocene water-bearing layers appear to have been deposited underlagoon fluviatile and beach environments, according to Zaghloul et al. (1979). These sediments reflect the start of the third Holocene Sea transgression phase, advancing primarily from the north and northeast. The Plio-Pleistocene aquifer's deposition regime is more influenced by Europe's glacial periods. During that time, the coastline was near the continental shelf's edge, and the Nile River created new channel deposits of sands and gravels with minor clay. The entire delta surface was thus sub-aerially exposed, resulting in clay oxidation and the production of gypsum and salt crusts duringarid phases (Geirnaert & Laeven, 1992). The sea level rose rapidly between 18,000 and 7500 years B.P., and the marine clays can be found up to 50 km inland. The sea reached its greatest extent at 5000 years B.P., after which it receded to its current shoreline. During the Holocene, regular flooding resulted in the deposition of thick layers of clay and siltuntil the High Dam construction in 1970, which eliminated the Nile's seasonal floods. The necessary information about this subject was collected from different sources such as (Butzer, 1967; El-Fayoumi, 1987; Fairbridge, 1967; Geriesh et al., 2015; Sestini, 1989; Shackleton & Opdyke, 1977; Shepard, 1963; Zaghloul et al., 1979). The Nile Delta witnessed significant changes during the Late Pleistocene due to major changes in sea level and climate conditions. The interglacial periods that separated the Middle Pleistocene from the Late Pleistocene caused a sea-level rise of roughly 13 m above its current level (Fiarbridge, 1967), undulating the sub-aerial delta plain and aggravating the distributaries on the lowlands. The last Pleistocene maximum transgression invaded most central lowlands at the period from 13,000 to

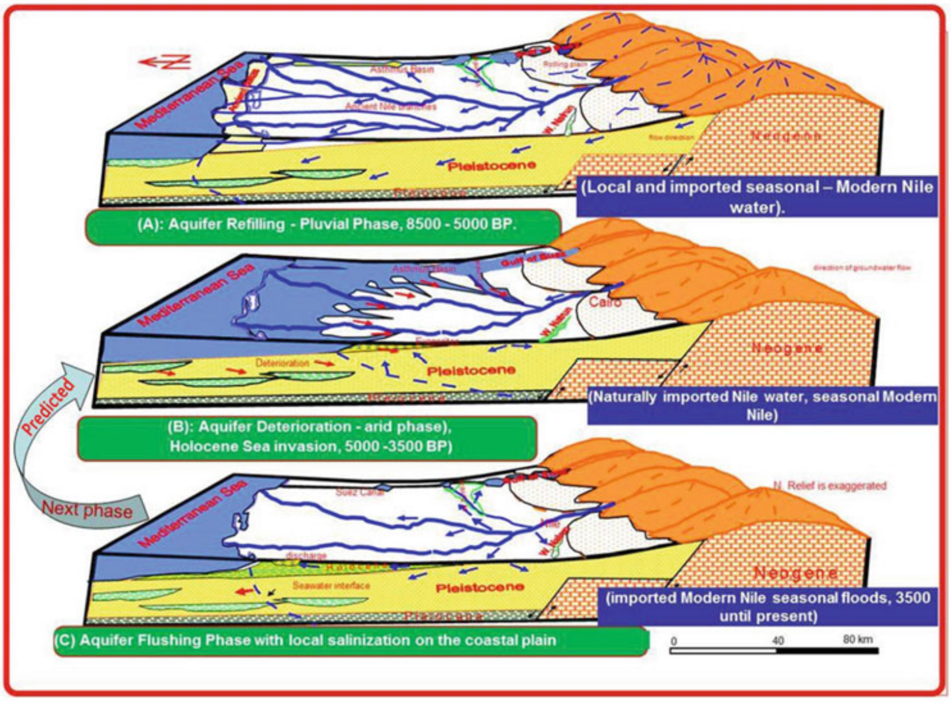

Fig. 6 3D model shows the paleo-hydrogeological history of groundwater recharge of the Nile Delta during the Holocene episode. Model (A) shows the aquifer refilling phase during the pluvial phase (8500–5000 B.P.), model (B) shows the aquifer deterioration phase during Holocene (5000–3500 B.P.), and model (C) shows the aquifer flushing phase from 3500 BP until the present. The blue curved arrow indicates that model (B) is expected to prevail as the next phase (modified after Geriesh et al., 2015)

6000 years B.P. It rose to a level varying between 9–15 m above the present sea level. Continuous Sea level fluctuation but within the range of its present Sea level characterized the latest Pleistocene period (Geriesh et al., 2015). The statistical analysis of radiocarbon dates for Saharan groundwater has supported the Holocene recharging period (Geyh & Jakel, 1974).Two or three different distinct short and humid phases have been discussed in the literature, with rainfall maximums ranging between 8500 and 5500 years B.P. (Rognon & Williams, 1977). There is also general agreement that one intermediate arid phase occurred approximately 7000 years B.P. and that no major humid period has occurred since 3500 years B.P. Inspection of the above-discussed paleo-hydrogeological history suggests that the most critical events to evaluate the existing groundwater aquifers are those that prevailed during the Holocene(Fig. 6). The Holocene time is characterized by two major climatic phases (El-Asmar, 1991; Geriesh, 2000; Geriesh et al., 2015). The older phase, which corresponded to the early Holocene, was distinguished by a warm-wet limate. Whereas, the younger one, 5000 to 3000 years B.P., was distinguished by arid climatic conditions associated with the Atlantic-sub-boreal phases. These two major climatic changes were also mentioned by Wendorf et al. (1977), Stanely and Maldonado (1977), Paulissen and Vermeersch (1987), Paepe and Mariolakos (1984), Van Overlop (1984) and were deduced from the post-glacial climatic curve of the Levant who pointed out the two climatic phases related to the Holocene. The older one (10,000–7500 B.P.) was humid, and the younger one was dry and related to the Atlantic stage. According to Rognon (1987) and Geriesh et al. (2015), there was a wet phase during the Holocene dated up to 6000 years B.P., followed by an arid phase during which gypsiferous deposits occurred formed at low land areas. It should be noted that groundwater age of the Pleistocene aquifer of the Nile Delta spans between 3000 and 8000 years B.P. (Geirnaert & Laeven, 1992; Geriesh et al., 2015).

2.3 Groundwater Recharge

Many authors have discussed the Nile Delta's hydrogeology and groundwater movement, including Shata and El-Fayoumy (1970), Geirnaert and Laeven (1992), Dahab (1994), Diab et al. (1997), Geriesh (2000), and Geriesh et al (2015). Groundwater recharge (Fig. 7) to the Pleistocene aquifer occurred via downward seepage from surface water (Nile branches and surface irrigation system) and by excessive irrigation in the traditionally cultivated lowlands and reclaimed desert fringes, (Geriesh et al., 2015). Rainstorms may also contribute in recharging, particularly in the unconfined aquifers of the southeast and southwest rolling plains.

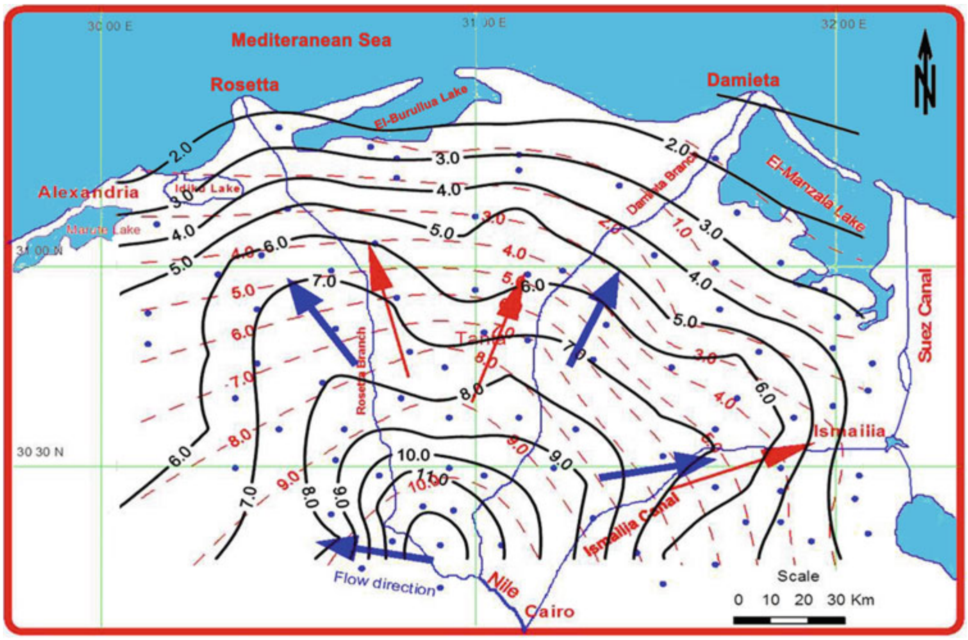

Fig. 7 Groundwater table map of both Pleistocene aquifer (black) and Holocene aquifer (red) of the Nile Delta (modified after Geriesh et al., 2015)

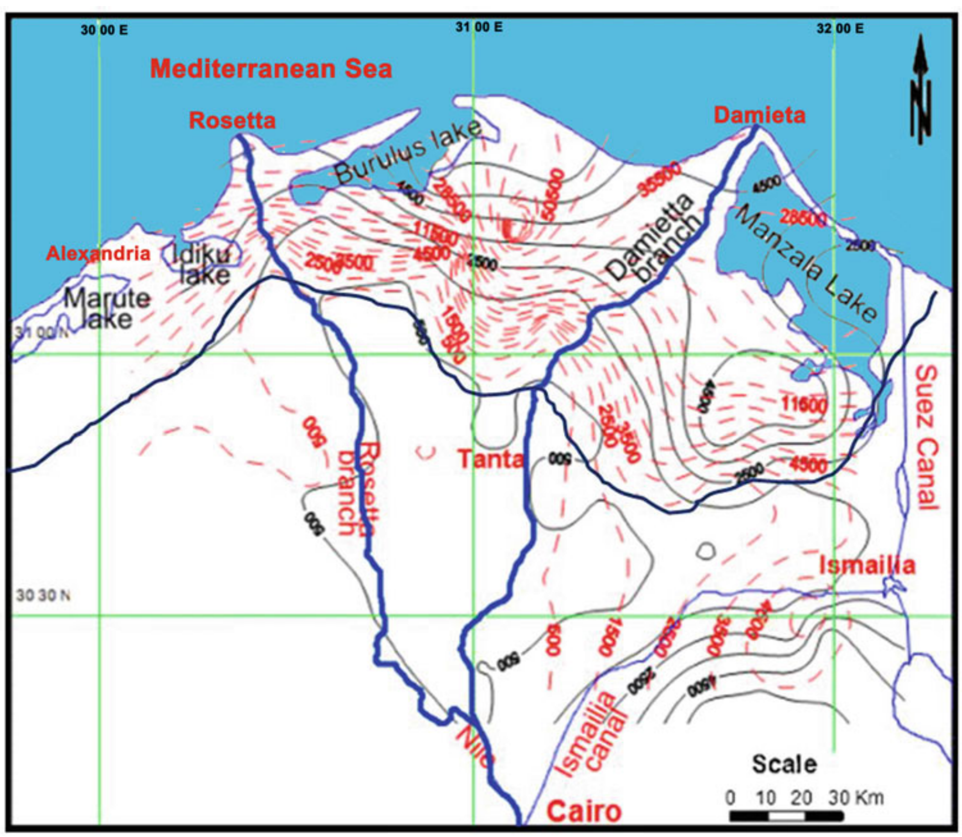

Fig. 8 Groundwater salinity in ppm of both Pleistocene aquifer (black) and Holocene aquifer (red) of the Nile Delta (modified after Geriesh et al., 2015)

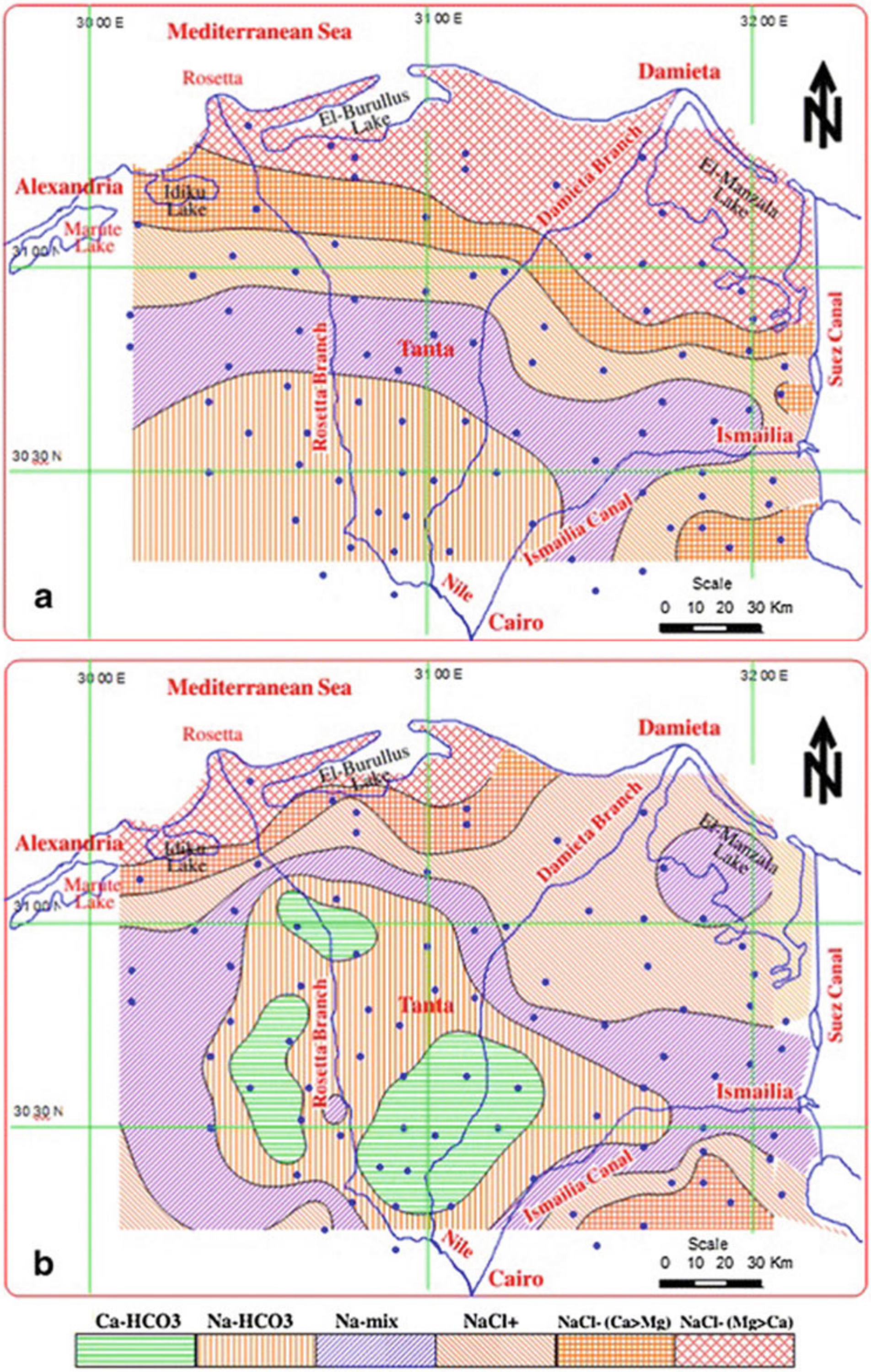

Fig. 9 Hydrochemical facies of both Holocene (**a**) and Pleistocene (**b**) aquifers of the Nile Delta (modified after Geriesh et al., 2015)

The general groundwater flow tis from south to north, eventually reaching the Mediterranean Sea and coastal lakes. Local groundwater flows from the Nile branches eastward to the Suez Canal and northern lakes (El-Manzala and El-Balah lakes), and westward to Wadi El Natrun (Fig. 7). The hydraulic gradient is quite low throughout the area, ranging between 0.1 and 0.3 m/km (Geriesh et al., 2015).

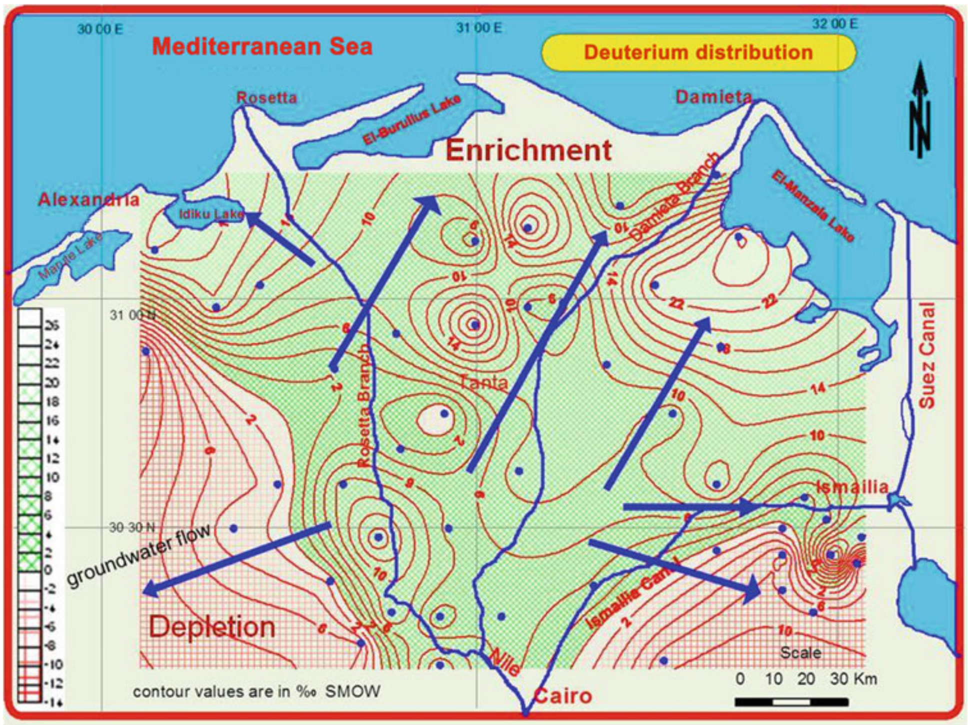

Fig. 10 Deuterium distribution map of Nile Delta aquifer (modified after Geriesh et al., 2015)

2.4 Hydrogeochemistry and Groundwater Quality

Many studies have been carried out about the hydrochemistry of the Nile Delta's groundwater aquifers including Shata and El-Fayoumy (1970), Abdel Mogheeth (1975), Diab et al. (1997), Geirnaert and Laeven (1992), Mansour (2015), and Geriesh et al. (2015), . According to these investigations, Nile Delta groundwater varies greatly in composition and salinity (Fig. 8). Salinity maps show two distinct zones, low salinity (TDS< 1000 ppm) nearby the flood plain and the Rosetta branch and high salinity (TDS > 10,000 ppm) along the coastal plain to the north and nearby the Suez Canal to the east (Fig. 8) are separated by a distinct interface as shown in Fig. 8 , which could be attributed to the change in lithologic facies from alluvial to fluviomarine salty facies and the impact of evaporation on the shallow water of the lowland areas to the north. The salinity contour lines around the Suez Canal and the attached lakes indicate discharge boundaries. Groundwater facies (Fig. 9) vary gradually from Ca-HCO_3 and Mg-HCO_3 close to the flood plain and Rosetta branch to Na-HCO_3 and Na-Mix to the west and the north and finally to Na-Cl and Ca-Cl toward the desert fringes and Na-Cl and Mg-Cl toward the coastal plain (Fig. 9). In the Na-Mix zone, Na exists as a surplus ion (Na>Cl), which may be attributed to the leaching process to a former brackish or saline water in this zone. Stable isotope analyses of the western Nile Delta flank indicated that most analyzed samples are arranged in a

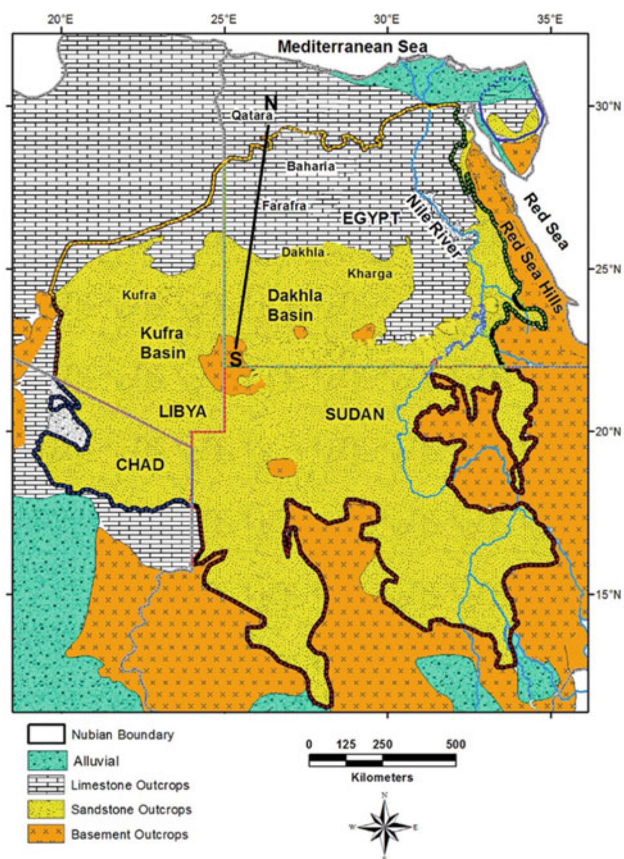

Fig. 11 Geographic distribution and regional geology of the Nubian sandstone aquifer system (NSAS) with delineating recharge areas (modified after Sultan et al., 2013; Thorweihe, 1982)

Table 1 Average aquifer thickness, transmissivity, and hydraulic conductivity of the NSAS in the Oases of the Western Desert (Hesse et al., 1987; Sefelnasr, 2002)

Area	Thickness (m)	Transmissivity (m^2/s)	Conductivity (m/s)
Kharga	1250	$3.2 * 10^{-2}$	$2.5 * 10^{-5}$
Dakhla	1750	$7.5 * 10^{-2}$	$4.8 * 10^{-5}$
Farafra	2600	$1.2 * 10^{-2}$	$4.2 * 10^{-5}$
Bahariya	1880	$8.8 * 10^{-3}$	$4.5 * 10^{-5}$
East Uweinat	430	$1.3 * 10^{-2}$	$2.3 * 10^{-5}$
Kufra	2850	$1.1 * 10^{-2}$	$5.9 * 10^{-5}$
Selima	260	$2.6 * 10^{-2}$	$1.3 * 10^{-5}$

Adapted from Hesse et al. (1987) and Sefelnasr (2002)

linear relationship between precipitation and Nile water (Awad & Nada, 1992; Geirnaert & Laeven, 1992; Geriesh et al., 2015). This might imply that the Nile is constantly releasing groundwater from the southern flood plain and Rosetta branch into the lowlands of Wadi El-Natrun (Fig. 10). This association shows that mixing of Nile water and fossil groundwater occurs where groundwater becomes more depleted in heavy isotopes as it moves toward the desert fringes, yet samples near Nile branches are enriched in heavy isotopes.

3 The Nubian Sandstone Aquifer System (NSAS)

The NSAS is Africa's most widespread fossil aquifer system, with a groundwater capacity estimated to be 150,000 Bm^3, equivalent to about 500 years of Nile River discharge (CEDARE, 2002; Salem & Pallas, 2002; Thorweihe, 1990; Thorweihe & Heinl, 2002). The NSAS is one of the world's largest transboundary aquifers, shared by Egypt, Libya, Sudan, and Chad (Fig. 11). It covers an area around 2.2 million km^2, including 828,000 km^2 in Egypt (38%), 760,000 km^2 in Libya (34%), 376,000 km^2 in Sudan (17%), and 235,000 km^2 in Chad (11%). The majority of the aquifer's water resources are located in Egypt and Libya, with Chad and Sudan having a lesser fraction (CEDARE, 2002; Thorweihe & Heinl, 2002). The NSAS has a maximum depth of 4500 m and a hydraulic head varying from 570 m above mean sea level west of Darfur in Sudan to -78 m below mean

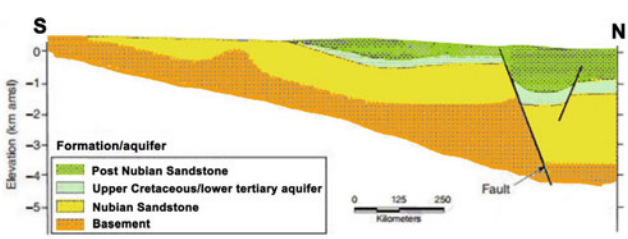

Fig. 12 Geologic cross-section of the Nubian sandstone aquifer system from S to N along the western desert of Egypt (modified after Thorweihe, 1990)

sea level in Egypt's Qattara Depression (Sefelnasr et al, 2015). The freshwater layer's thickness ranges from 200 m east of Uweinat to 3500 m northwest of El-Farafra Oasis (RIGW, 1990), with medium to good hydraulic properties, as shown in Table 1. The following are the actual withdrawal rates from the NSAS as of 2012: Egypt: 1029 Mm^3/yr; Libya: 851 Mm^3/yr; Sudan: 406 Mm^3/yr; and Chad: 1 Mm^3/yr (Ahmed, 2013). The NSAS water storage in Egypt is believed to be roughly 40,000 Bm^3, but unfortunately this is not renewable due to the low recharge of groundwater in the Western Desert (El-Rawy et al., 2020; Heinl & Thorweihe, 1993). The NSAS was initially used on a wide scale in Egypt in 1960, in the main Oases of the Western Desert, with total groundwater extraction projected to be in the billions of cubic meters (CEDARE, 2014).

3.1 Geologic and Hydrogeologic Settings

The Nubian Aquifer System (NSAS) is made up of Paleozoic and Mesozoic deposits that overlying the Precambrian basement complex that underlies the entire NSAS basin. The NSAS is composed of medium to coarse sandstone formation (Fig. 12). Because of different water-bearing strata, the NSAS contains two distinct groundwater systems: (1) the Lower Nubian Aquifer System (LNAS), which is over 400 m thick and is under unconfined condition below the 25th latitude, but confined in the north; and (2) the Post Nubian Aquifer System (PNAS), which often occurs north of the 25th latitude and overlies the (LNAS) in Egypt's Western Desert and northeastern Libya.

The NSAS is divided into three major sub-basins:

- Kufra sub-basin in northeastern Chad, northwestern Sudan, and Libya.
- Dakhla sub-basin in Egypt.
- Northern Sudan Platform sub-basin in northern Sudan.

At the western desert, the aquifer is mostly made of hard ferruginous sandstone with thick shale and clay intercalation and ranges in thickness from 140 to 230 m (Sefelnasr et al., 2015).

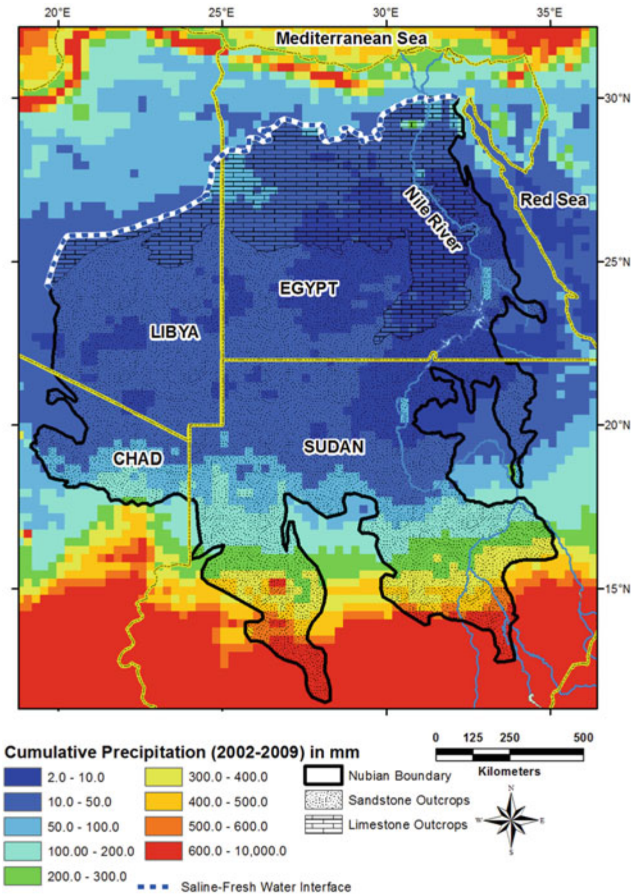

Fig. 13 Cumulative average precipitation rate derived from three-hourly Tropical rainfall measuring mission (TRMM) data over NSAS during the period from 2002 to 2009(Sultan et al., 2013)

The Upper Cretaceous Nubian Sandstone Aquifer, which lies near the land surface in some regions, is the major aquifer in the Western Desert. The Late Paleocene and Early Eocene Esna Shale cover most of it, followed by a highly broken Eocene limestone (Geriesh et al., 2020). In West of Aswan, an erosional unconformity can be detected, and thick fluvial deposits from various origins and ages cover the Nubian Sandstone Aquifer. Despite its enormous size, the NSAS is regarded a closed system since it is naturally bounded to the west and south by mountainous outcrops of the Kordofan Block, Ennedi, and Tibesti, and to the east and southeast by Nubian Shield mountain ranges (Fig. 11). The Saline-Freshwater Interface is the natural northern boundary of the Nubian Sandstone Aquifer System, and its location is assumed to remain spatially constant (Fig. 12). Most groundwater in the NSAS is meteoric in origin (i.e., atmospheric), while minor part is derived from magma (Juvenile water). Low irregular rainfall, constant drought, land degradation, and desertification characterize the region's climate. Rainfall occurs most frequently between June and October, with an annual average of less than 25 mm in the far north. It usually increases to the south, with an average of 200 mm near Khartoum, although its distribution is highly varied (Fig. 13).

3.2 Aquifer Recharge and Hydrogeochemistry

Several studies relate the recharge of the NSAS to Nile River along its eastern borders, groundwater flow from the Blue Nile, and local rainfall on ephemeral watersheds in the mountainous terrains. Due to groundwater discharge into depressions, evaporation potential in regions with shallow groundwater table, and upward leakage into confining beds, low values of infiltration rate were obtained when compared to natural groundwater flow. As a result, under current climate conditions, the NSAS is considered as a non-renewable groundwater resource (Mirghani, 2012). It is also believed that the NSAS receives current recharge regionally from southern borders (Sudan and Chad) and locally (west of Nasser Lake and Aswan) through significant fractures and joints, as well as in the northern regions of Sinai Peninsula where exposed aquifer rocks receive high amounts of rainfall (e.g., Geriesh et al., 2020; Robinson et al., 2007; Sultan et al., 2013). The NSAS has an isotopic signature that is depleted, with ^{18}O levels ranging from -9.8 to -10.99 ‰ and ^{2}H values ranging from -77.6 to -87.8 ‰ (Abouelmagd et al., 2012, 2014; Aly et al., 1989; Geriesh et al., 2020; Hamza et al., 1982; Swailem et al., 1983). Further studies on fossil groundwater from the Nubian Aquifer in the Sinai Peninsula revealed that their radiocarbon ages ranged from ~ 24,000 to ~ 31,000 years B.P., indicating recharge during and/or before the Last Glacial Maximum (Abouelmagd et al., 2014). These isotope signatures may have indicated paleo-water replenishment during the Late Pleistocene (Geriesh et al., 2015). Nile water seepage; local rainfall on aquifer outcrops, and local infiltration from precipitation during previous wet periods are also sources of recharge. Groundwater varies from fresh to somewhat saline (salinity ranges between 240 and 1300 ppm). Low salinity and, in some cases, super-fresh groundwater characterize the majority of the water-bearing Nubian sandstone layers. in many areas such as the Farafra Oases and deep layers in the Siwa Oasis. The Na-Cl and Na-Cl-HCO_3 groundwater types represent the Nubian Sandstone aquifer's old meteoric water (Geriesh et al., 2020)

3.3 Groundwater Flow and Aquifer Characteristics

Groundwater flow in the NSAS is generally from South to North at Dakhla Basin in the Western Desert (Sefelnasr et al, 2015) and Sinai Peninsula (Abouelmagd, 2014). However, because the Uweinat-Aswan uplift impedes groundwater flow from south to north, the flow in the Kufra basin is from southwest to north and northeast (Sultan et al., 2013). The groundwater ages range from less than 30,000 years in the south to one million years in the north (Sturchio et al., 2004). The age increases to the north, and there is local groundwater recharge west of Lake Nasser and the Toshka plain to the Nubian sandstone aquifer that extends for less than 5 km in length (Geriesh et al., 2020; Masoud et al, 2013). Findings indicate strong correlation between low-salinity groundwater and the spatial distribution of fluvial and structural features. Low-salinity water can be found near alluvial fans especially in the southwest reaches of structurally enclosed streams, . The presence of low-salinity water in wells near structures emphasizes the need of structural knowledge in understanding groundwater flow patterns (Geriesh et al., 2020; Koch et al., 2012; Robinson et al., 2007). Between the late 1950s and the early 2010s, when the New Valley project was initiated, there was an urgent need to examine the underground reserves of the land reclamation areas. The following groundwater extraction results were obtained from all models in the region:

1. El-Bahariya Oases drawing areas were in the range of 30 Mm^3/yr (1990) and could be increased to 143 Mm^3/yr (2000).
2. Areas of the Farafra Oasis: The current pumpage is in the range of 131 Mm^3/yr in 1996 and can be increased to about 469 Mm^3/yr.
3. El-Dakhla Oases: The current abstraction is 185 Mm^3/yr and can be increased by 217 Mm^3/yr, while reports from the Ministry of Irrigation indicate that a potential for an increase of 76 Mm^3/yr could be added.
4. El-Kharga Oases: The current figure is estimated at 110.3 Mm^3/yr, and the report of the University of Berlin advises against increasing.
5. South of Baris Oasis, there are no studies of the possibility of land reclamation, and it is recommended to develop a hydrogeological model to include this area using data and information that can be obtained from existing wells, wells being drilled, and future wells in this area.
6. East Uweinat: Based on numerical modeling for the Eastern Uweinat region, three scenarios were simulated for the exploitation of the NSAS water. These scenarios build up based on keeping the potentiometric water level do not complete the model area's aquifer's complete depletion. A realistic plan would be based on lowering the water level at a maximum drop to a depth of fewer than 100 m. Egypt's total storage capacity is estimated to be 40,000 Bm^3/yr; however, usage of this resource is dependent on pumping costs and economic returns over a short time . In the Western Desert (East Uweinat, Farafra, and Dakhla Oases), the total potential groundwater withdrawal is roughly 3.5 Bm^3/y (El Alfy, 2014). In central Sinai, the NSAS aquifer has potential for further development (200–300 Mm^3/y, JICA, 1992), while, in the Eastern Desert, the aquifer potential ranges between 50–100 Mm^3/y.

If large-scale depletion continues in the Western Desert, the aquifer will be stressed and the water level will fall to the point of being depleted. Superior quality water with relatively high iron and manganese concentrations is pumped from the Nubian Aquifer in several regions across the Western Desert and the Sinai Peninsula. The salinity of groundwater varies vertically and horizontally. Groundwater abounds with high potentiality in four water-bearing strata separated by interbedded shale and clay beds in the El-Bahariya Oasis, with its flow patterns varying from SW to NE (Khaled & Abdalla, 2013). In Kharga and Dakhla Oases, salinity drops with depth from more than 1000 mg/l in the top water-bearing layer to 200 mg/l in the lowest water-bearing layer . The top water-bearing layer near the saltwater boundary in the Siwa region includes freshwater (200–400 mg/l), but the deeper water-bearing layer contains hypersaline water (up to 100,000 mg/l). Because of the high quantities of free CO_2 and H_2S, as well as the low redox potential, this groundwater is particularly corrosive. The high iron and manganese concentrations (2–20 mg/l) found in Farafra, Bahariya, and other locations cause well-screen clogging (Korany, 1995). Furthermore, groundwater radium pollution beyond the maximum contaminant limit (MCL) of drinking water has been recorded in the Nubian Aquifer in the Western Desert (Sherif & Sturchio, 2021) and the Sinai Peninsula (Sherif et al., 2018).

4 The Fissured Carbonate Rock Aquifer (FCRA)

Over half of Egypt's land area is covered by the FCRA, which stretches from the Sinai to Libya (see Fig. 2). It has several natural springs because it functions as a confining layer on top of the NSAS. Uncertainty surrounds the aquifer's recharge, and its potential is not well understood (MWRI, 2013). Despite accounting for at least half of Egypt's entire surface area, the FCRA is the least studied and utilized. It is mostly found in Egypt's Western Desert's northern and central sections. The aquifer's recharge is dependent on upward seepage from the deeper Nubian Sandstone aquifer and, occasionally, local precipitation. Its thickness extends from 200 to 1000 m, with an estimated 5 billion m^3 of exploitable brackish water in the fissured carbonates (MWRI, 2013).

4.1 Geologic and Hydrogeologic Settings

Three formations may be distinguished within the carbonate complex:

- Lower Formation: Upper Cretaceous,
- Middle Formation: Lower and Middle Eocene,
- Upper Formation: Middle Miocene.

An upper fractured limestone complex with a thickness varying around 650 meters (Upper Cretaceous to Middle Miocene) and lying irregularly on the NSAS is discovered in wells dug in the Siwa Oasis. There are 200 or more natural springs scattered around the top of the Middle Miocene fissured limestone outcrop, with a daily flow of about 200,000 m^3 and salinities varying from 1500 to 7000 ppm. At Gebel Anguilla and the EI-Farafra Oasis, the aquifer's water levels range from 62 to 80 m above mean sea level, and various wells tapping it (Khalifa, 2014). With extremely few exceptions, direct rainfall, and surface runoff, the FCRA is mostly recharged by upward groundwater leakage from the underlying Nubian Sandstone Aquifer via existing deep faults (EI-Ramly, 1967; II Nouva Castoro, 1986). The Upper Cretaceous aquifer in central Sinai is distinguished by a thick section that rises over 800–1000 m and is mostly made of chalk, chalky limestone, marl, dolomite, dolomitic limestone, and shale (Abdalla & Scheytt, 2012). Numerous limestone, marl limestone, and marl layers make up the Eocene rock. Near the outcrops of the El Egma and El Tih Plateaus, the thickness of these strata progressively reduces southward to about 200 m. Salinity levels in groundwater climb northward and range from 3800 to 5000 mg/l (JICA, 1992). The yearly recharge for the Sinai Peninsula is anticipated to reach 76 Mm^3 (JICA, 1992). The Upper Cretaceous aquifer is contained by a down-faulted tertiary-age rock that stretches from the district's central region to the north of Gabal Maghara and Gabal EI-Halal districts. The free to semi-confined properties of this aquifer system in the center of Sinai are accompanied by modest discharge rates through several shallow wells and natural contact springs. The groundwater flows from the southern terrains towards the northern lowlands. A typical SE-NW flow with a hydraulic gradient of 0.0035 is present. In southern Sinai, intercalation of Cenomanian, marly limestone, and shale occurs downstream of Wadi Feiran, forming a confining unit (aquitard) for the underlying NSAS. The aquifer thickness and top confining unit vary from 100 m near its outcropping sections along the eastern portions to approximately 450 m westwards with the Wadi exit to the Gulf of Suez (Geriesh & El-Rayes, 2000). The aquifer is discharged westward into the Gulf of Suez through natural springs near the coastline (e.g., Hammam Pharaon and Ayoun Moussa). Marine Miocene carbonate rocks, which may influence water quality due to their high evaporite concentration, underlie the aquifer's furthest downstream reaches. Hydraulic conductivity in central Sinai is 18.4 m/day, while transmissivity is 663.7 m^2/day (Abdalla & Scheytt, 2012). Karstified sedimentary formations are the only places where groundwater occurs and flows freely. The aquifer's groundwater potential is growing due to fault and fissure systems. The transmissivity of Helwan, south of Cairo, ranges from 4.6 10-3 m/s to 9.3 10-3 m/s. The degree and continuity of fractures affect well productivity, which varies by geography (Abdalla & Scheytt, 2012). The fissured limestone possesses karstic properties due to groundwater circulation through many warm springs, and salt concentrations can reach > 5000 ppm (Abdalla & Scheytt, 2012). Well discharge rates in the Siwa Oasis, Western Desert, range from 5 to > 300 m^3/h. Salinity varies according to the recharge area's location and the kind of rock found in the water-bearing strata. Freshwater only appears if the aquifer is significantly recharged with freshwater from wadi infiltration or upward leaking from the Nubian Aquifer into overlying carbonate aquifers. Groundwater in the western desert's Farafra Oasis is extremely fresh and has a salinity of less than 1000 ppm. Salinity ranges from 2000 to 5000 ppm in the southern part of the northern plateau, and it rises to more than 10,000 ppm in the north, where the Dabaa Shales cover the aquifer (Joint Venture Qattara, 1979). The Middle Eocene through the Pleistocene and Holocene are covered by the El Minia Governorate's FCRA. Eocene rocks provide a wide variety of limestone formations (fissured, chalky, and silicified). An Eocene (limestone) aquifer known as the Samalut Formation is made up of hard, white, and abundantly fossiliferous limestone that is intercalated with shale and marl. A fault network that affects the Eocene aquifer could have an impact on how the aquifer recharges. Under porous alluvium layers, groundwater is present under unconfined condition. The Eocene aquifer's water depth varies between 25 and 120 m west of the Nile and 6 and 153 m east of the Nile. The eastern bank of the Nile is where you will most observe an increase in water depth from north to south. Recharge sources for the Eocene aquifer include current precipitation percolation, periodic flash floods, downward leakage from the upper Quaternary aquifer, and perhaps upward leaking from the Nubian sandstone aquifer. In the northern part of the Eastern Desert, thick wide multi-horizon successions of carbonate rock facies, sandstones, shale, and clay constitute the main representation of the fractured limestone and sandstone aquifers. The Middle Miocene aquifers have hydraulic conductivity, storativity, and transmissivity values of 4.31 m/d, 1.2×10^{-3}, and 70 m^2/d, respectively (El-Ghazawi and Abdel Baki 1991).

5 The Fissured Hard Rock Aquifer (FHRA)

Non-volcanic (plutonic) igneous and metamorphic rocks are usually referred to as crystalline rocks according to their origin from the crystallization of magmas and re-crystallization of other rocks. They occur as intrusive amidst other rocks, as extrusive on the surface, or as large bodies or plutons, crystallized at considerable depths. The aquifer runs through the Red Sea hills and the southern Sinai Peninsula, where exposed schist, gneiss, and granite rocks (see Fig. 2).

5.1 Aquifer Geology and Hydraulic Characteristics

The FHRA is primarily made of granite, granodiorite, and gabbros. Rhyolite and andesite dikes are abundantly distributed throughout the Red Sea and southern Sinai (Fig. 14). The composition of crystalline rocks varies from acidic to basic depending on the silica amount and composition of feldspars and ferromagnesian minerals. The Pre-cambrian basement aquifers are oucropped along most of the investigated watershed area, as well as in southern Sinai (Fig. 14). The fractured and worn crown (up to 5 m depth) of these rocks serves as the primary recharging location for the basement wadi filling aquifers and is regarded as a water collector from a hydrogeological standpoint, with groundwater occurring largely in the joints and cracks within these rocks (Geriesh & El-Rayes, 2000). The joint density, the number of tapped fault zones, and the terrain of the immediate area around the well site all affect the wells' output (El-Rayes, 1992). Southern Sinai's Precambrian and Cambrian rocks get an estimated 52,000 m^3/d of recharge (Dames & Moore, 1985). Fresh, solid, unaltered, and unfractured specimens of crystalline igneous and most metamorphic rocks have primary porosities that rarely exceed 2%. Many rock types are, therefore, impervious and impermeable. Secondary porosity and permeability are imparted to these rocks by weathering and fracturing. The permeability of crystalline rocks varies greatly depending on the degree of weathering, the composition of the weathered components, and the intensity of fracturing and open spaces in the cracks. The hydraulic conductivity of the upstream sediments (3–6.8 m/d) increases in tandem with the wadi filling deposits in the basement terrains. The hydraulic conductivity of downstream sediments, on the other hand, is the lowest (< 0.5 m/d), which can be related to the abundance of carbonate rocks and large mud proportions in most downstream streams. Also, hydraulic conductivities of the trough areas (i.e., basins) are much lower than those areas of the steeply sloped stream gradients (Geriesh & El-Rayes, 2000). The depth of the water table fluctuates significantly throughout the FHRA due to its undulating topography. In the Wadi Feiran basin in the southern Sinai, the fractured basement rocks aquifer has an estimated average transmissivity of 57.3 m^2/day and a specific yield of 0.017. (Abouelmagd, 2003). The FHRA may be divided into the following three units based on the hydrogeological significance and areal distribution:

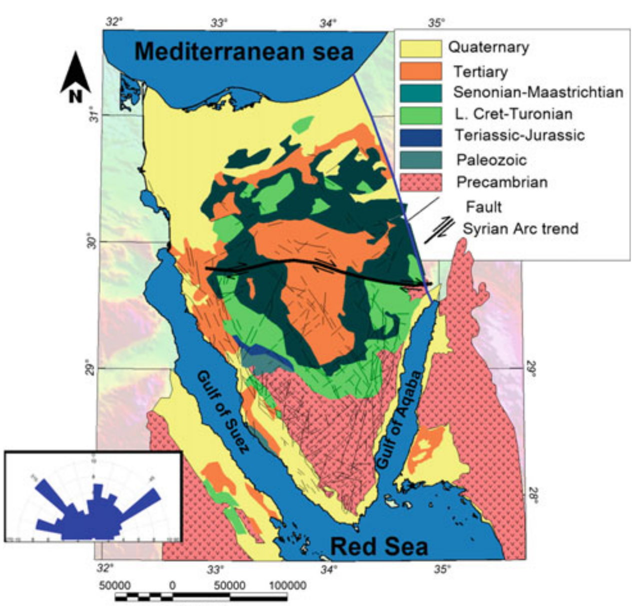

Fig. 14 Geology of the crystalline province of Southern Sinai (after Ginzburg et al., 1979; Neev, 1975)

1. Pre-Cambrian fractured basement rocks.
2. Quaternary alluvial deposits.
3. Volcanic dykes and sills.

Because of the decrease in the porosity and specific yield with depth, water held in storage and water potential for extraction from a unit volume of basement rock decrease with increasing depth. Although the worn and interconnected fracture zones form a continuous aquifer with hydraulic continuity, the heads in individual zones might vary, lowering in recharge areas and increasing in discharge areas. The crystalline aquifers are affected by lithologic and structural control. Depth to water levels broadly follows the topography. Where the rocks are highly permeable and where the local base level of erosion lies deep, the water level may also be deep due to quick water drainage. If there are several flows, perched aquifers may be formed above the impermeable horizons of different flows. The alternating succession of permeable and dense horizons in volcanic rocks form a multi-aquifer system. Wadi filling deposits in most basement hydrographic basins act as good collectors for rainfall and flash floods that occur in the basement terrains' watershed zones.

Aquifer storage and depths of these wadi filling deposits depend mainly on the underlying basement topography and wadi crossing dykes (Geriesh et al., 2004; Shendi & Abouelmagd, 2004). The topmost weathered, jointed, volcanic dykes, and the vesicular layer form phreatic aquifers. The inter-flow permeable horizons occurring below the massive zone comprise confined aquifers, with interconnections to a varying degree, depending on the nature of layers in between. Small, thin, intrusive bodies like sills and dykes emplaced far away from the volcanic vents may have congealed rapidly and developed joints within the intrusive body as well as in the host rocks. When bordered by less permeable host rock, weathered dykes can operate as preferred flow conduits, but impermeable dykes can significantly contribute to impounding groundwater flow, acting as barriers, and causing local aquifer compartmentalization (Houben et al., 2018; Mohamed et al., 2015).

5.2 Groundwater Recharge and Quality

Precipitation is considered as the main source of groundwater recharge in the FHRA. Massive runoff along the main wadis toward the Red Sea may be the result of heavy rainfall in the Eastern Desert. However, a significant amount of rainfall can percolate downward and be stored in the cracked basement rocks via open areas and fracture systems. Groundwater flows downward through the cracks because of the hydraulic gradient and gravity force to replenish both the Phanerozoic sedimentary aquifers and the Quaternary alluvial deposits that fill the hydrographic basins and plains (e.g., El-Qaa Plain in southern Sinai). In southern Sinai, the FHRA is also recharged by small infiltrating rainwater quantities (El-Rayes, 1992), so water flows through fractures, joints, and voids. Hand-dug wells provide a limited quantity of water with good salinity along with the wadi filling deposits in most southern Sinai and Eastern Desert areas. Deep wells, such as the El-Baramya Well in the Eastern Desert, provide a plentiful supply of water. The water quality ranges between 300 and 800 ppm in the watershed areas and between 1800 and 2500 ppm in the downstream areas (Geriesh & El-Rayes, 2000; Geriesh et al., 2004). The groundwater quality of the Pre-Cambrian basement aquifer is significantly influenced by the geochemistry of the host rock and the surrounding area. In the northern region of the Eastern Desert, the quality of the water ranges from fresh to brackish. Salinity levels vary between 600 and 3500 ppm. The most dominant ion orders in the headwaters are Ca > Na > Mg and $HCO_3 > Cl > SO_4$. Because of a possible ion exchange mechanism, Na replaces Ca and Cl, and SO_4 replaces HCO_3. The arrangement of ion dominance changes downstream to Na > Ca > Mg and $Cl > HCO_3 > SO_4$. The fractured basement aquifer is characterized by the Ca-bicarbonate facies, while the Quaternary aquifer of the wadi filling deposits is characterized by the Na-mix facies (Geriesh & El-Rayes, 2000). The biochemical interferences could change water facies in the shallow dug wells found in hard rock (Geriesh et al., 2004). The presence of algae in the shallow dug wells water indicates an environment rich in nutrients and organic matters that help grow these algae. Algae create an oxidizing environment as a result of the photosynthetic process during which oxygen increases. Moreover, the alkalinity of water also increases, consequently reacting with Ca ions to form calcite that precipitates once the water reaches the saturation state. On the other hand, the presence of bacteria and organic matter in some of these wells reduces SO_4 ions and, consequently, increases HCO_3 content. This biochemical interference may explain the enrichment in HCO_3 ions and the decline in Ca/Na ratio along the upstream reaches in basement terrains, characterized by low salt contents.

6 The Moghra Aquifer

In Moghra aquifer, groundwater flows westward from the northwestern desert to the Qattara Depression (Fig. 2). Rainfall and lateral inflow from the Nile Delta aquifer recharge the Moghra aquifer. Only freshwater is present, and salinity increases in the north and west (Khalifa, 2014). The Nile Delta aquifer is thought to recharge the Moghra aquifer at a rate of 50–100 Mm^3/yr. Evapotranspiration from the Qattara Depression in the southwest and Wadi El-Natrun in the west leads to natural discharges.

6.1 Aquifer Geology and Hydrogeologic Settings

The Moghra aquifer is made up of Lower Miocene sandstone with claystone and siltstone intercalations that shift to shale as you get closer to the Mediterranean (Fig. 15). The aquifer's base is Oligocene basalt and Dabaa shale. The aquifer slopes from ground surface level at Cairo to 1000 m below mean sea level west of Alexandria. (Khalifa, 2014). Its thickness is thinned in the north and west to overlap with the Marmarica Limestone and ranges from 200 m in Wadi El-Farigh to 800 m in the Abu El-Gharadig basin east of the Qattara Depression. Both fossil and renewable water can be found in the Moghra aquifer. The Moghra aquifer exists under phreatic condition, with groundwater table varying from 60 m below MSL in the west in the Qattara Depression to 10 m above MSL near the Nile Delta aquifer boundary. With an average gradient of less than 0.2 m/km, the hydraulic gradients are quite gentle. The permeability of the aquifer varies from less than 1.0 m/day in the Qattara area and along the coast to 25 m/day east of Wadi El-Farigh. In m^2/day, the transmissivity ranges from 500 to 5000. Groundwater is

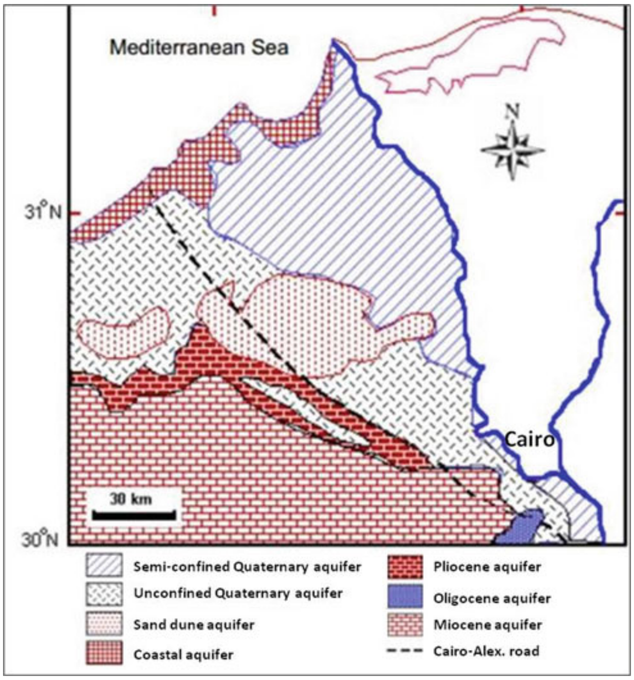

Fig. 15 Geology of El-Moghra aquifer (modified after RIGW, 1991)

utilized to irrigate more than 60,000 Feddans (252 Mm^2) in Wadi El-Farigh, and irrigation wells yield outputs of more than 200 Mm^3/y at the water-table/ground-surface junction (Youssef, 2012). The Qattara and Wadi EI Natrun depressions, where multiple springs discharge 706 Mm^3/y, are the sites of substantial evaporation. Aquifer discharge occurs by lateral seepage into carbonate rocks west of the Qattara Depression (El-Rawyet al., 2020).

6.2 Aquifer Recharge and Groundwater Quality

The Nile Delta Aquifer, the Marmarica Limestone Aquifer, the direct rainfall on the aquifer's outcrops, and the upward seeping from the underlying Nubian Sandstone Aquifer are the four sources of recharge for the aquifer (El-Sayed & Morsy, 2018; Geriesh et al., 2015; Salah & Samah, 2018). Groundwater predominantly flows west from the Nile Delta aquifer to Wadi El-Natrun and the northern parts of the El-Moghra aquifer with a gentle hydraulic gradient of around 0.003 (Gerish et al., 2015). The water salinity in the El-Qattara depression varies from less than 1000 (ppm) in the east (next to the primary recharge area) to more than 5000 ppm in the west (near the main discharging area). The water type exhibits mixed facies of renewable and fossil water recharge from the Nile in the east (Geriesh et al., 2015). The saturated thickness varies from 70 to 700 m (RIGW, 1991). While conditions are unconfined in the south, they are confined as you move north. While the present yearly discharge is anticipated to be 200 million m^3, the annual production surpasses one billion cubic meters. A hydraulic gradient of 0.2 m/km directs groundwater flow farther westward into the El-Qattara Depression. Permeability drops from 25 m/day in Wadi El-Farigh to 1 m/day on the Mediterranean coast in the north. The transmissivity ranges from 500 to 5000 m^2/day, (Salah & Samah, 2018). The anticipated yearly lateral leakage from the Nile Delta aquifer to the Moghra aquifer is about 50–100 Mm^3

Only in Wadi El-Farigh, on the aquifer's eastern boundary, can fresh groundwater exist (500–1000 ppm), and salinity rises north and westward until it reaches > 5000 ppm (Salah & Samah, 2018). As water levels drop, salinization and nitrate contamination caused by over-pumping along the aquifer basin impair water quality and its viability for drinking, residential, and agricultural uses. The hydraulic head falls off in the Wadi El-Natrun region by around 0.5 m/y due to over pumping from wellsTo maintain this aquifer, corrective actions must be taken, including decreasing the number of pumping wells, decreasing intial and operational well time, s, and installing drip irrigation systems (Youssef, 2012). According to isotopic fingerprints, the west of the site had a major depletion, while there is a gradual enrichment towards the northern and eastern Nile Delta reaches (Geriesh et al., 2015).

7 The Coastal Aquifer

Direct rainfall recharges the coastal aquifer, but the presence of saline water under the freshwater lenses restricts abstractions (MWRI, 2013). Quaternary sediments are the major unit of the coastal aquifer. Its thickness ranges from 30 to 90 m, and the groundwater along the eastern Mediterranean coast is generally brackish (> 3,000 ppm).

7.1 Aquifer Geology and Hydraulic Properties

The hydrogeology of the northern Mediterranean coast has been studied by RIWR (1995), Ghodeif and Geriesh (2003), Geriesh et al. (2004), Geriesh et al. (2015a), and Arnous et al. (2015, 2017). They described the physical and chemical parameters of the northern coastal aquifers and further discussed the problem of seawater intrusion. According to these studies, the groundwater exists in three rock units: (1) the sand dune unit; (2) the old beach sand unit, and (3) the calcareous sandstone (*Kurkar Formation)* unit to the east and the calcareous sandstone aquifer to the west of the Mediterranean shore line (Fig. 16). Most of the water well fields tap the last two aquifer units. The sand dune aquifer consists of well-sorted sands attaining 5–15 m in thickness and extends horizontally to cover most of the eastern parts of

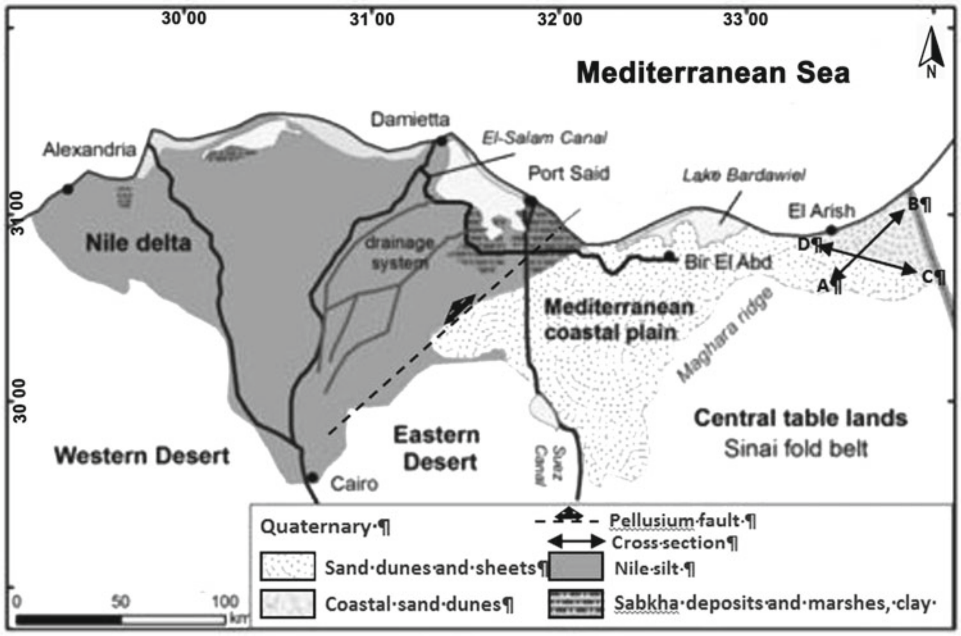

Fig. 16 Geology of the Mediterranean coastal aquifer (modified after CONOCO, 1987)

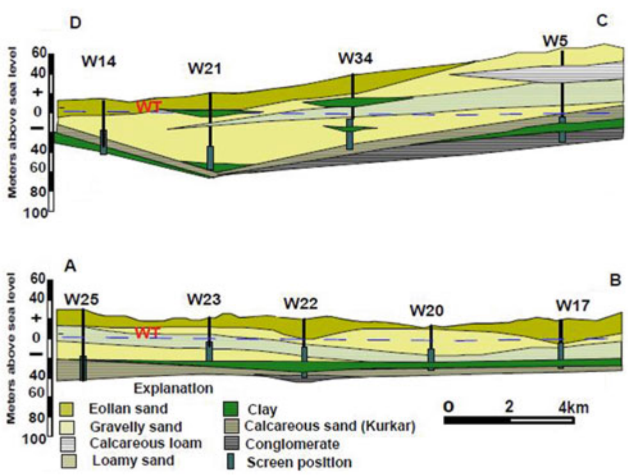

Fig. 17 Hydrogeologic cross-sections along the Mediterranean coastal aquifer, northern Sinai, A-B and D-C of Fig. 16 (modified after Geriesh et al., 2004)

the northern Sinai Mediterranean coast (Fig. 17). They vary in thickness between 30 and 90 m. The good hydraulic conductivity and high porosity of the sand dunes characterize its good potentiality. The calcareous sandstone aquifer is divided into two layers: upper alluvial and lower old beach sands. Groundwater capacities in the northwestern Sinai are more restrained than in the northeastern area. The latter is covered in sand dunes, which make up the principal aquifer. Water is found there between 1 and 7 m below the surface, where it is present as a thin layer on top of the main saline water (El-Shazly et al., 1975). As a result, pollution poses a serious threat to this valuable water supply. Two transverse zones might be created from the western coastal area. The groundwater potentiometric surface is greater than the ground surface of the northern El-Tina plain, a part of the Nile flood plain coastal aquifer made of silty clay intercalated with salts, evaporites, and sands. The groundwater is primarily salty and unsuitable for irrigation (Fig. 16). Eastward, the aquifer's composition transforms into silty clay and clayey silt that is covered in a salt crust (Arnous et al., 2017; El-Rayes et al., 2017; Geriesh et al, 2015a). The Pelusium line and the coastal hinge fault are tectonic features that control the Sinai Mediterranean coast. A section of the Egyptian Mediterranean coast zone to the east of Port Said occupies El-Tina plain and its environs. The Mediterranean coast's dynamic processes include sea components (waves, currents, and tides), wind, and sometimes rainfall. Quaternary sediments cover the southern area and control the land sculpturing rate (degradation and aggradations processes). The hydraulic properties of the Quaternary aquifers vary from north to south, where the hydraulic conductivity varies between 1.25 and 12 m/d along the southern zones to 38 and 64 m/d along the sand dune belt to the north. The transmissivity varies between 86 and 690 m^2/d at the south to 700 and 1910 m^2/d in the north, whereas storativity (S) varies between 0.01 and 0.05 at the south to 0.15 at the northern sand dunes zones (RIWR, 1995).

From these hydraulic characteristics, it could be concluded that the sand dune and old beach aquifers in the north are highly productive and highly vulnerable to contamination relative to the Kurkar aquifer in the southeast. The three Quaternary aquifer units are hydraulically connected. Along El-Tina plain, the coastal aquifer is composed mainly of fluviomarine sediments, and therefore, its water quality is highly saline (Geriesh et al., 2015a).

The Miocene (Rudies Formation) and Nubian Sands comprised groundwater wells excavated in the coastal aquifer along the Red Sea Coast in Wadi Dara, Ras Ghareb, and Ras Shoqeir. Depth of groundwater formations reaches 600 to 900 m from the land surface. The Aquifer's thickness ranges from 90 to 140 m. Water depths vary from 30 to 50 m.

7.2 Groundwater Recharge and Quality

The main source of groundwater recharge in the coastal aquifer is rainfall. It can reach 300 mm per year near the Sinai Shore and 170–200 mm per year along the Nile Delta and western coast. About 10% of the rainwater feeds the Quaternary aquifers in the coastal area (RIWR, 1995). Sewage effluent and irrigation return flow from cultivated fields serve as supplementary recharge supplies for the shallow, highly vulnerable aquifers in the central and northern sand dunes belts, as well as the scattered agricultural lands along the Mediterranean coast zone (Geriesh et al., 2004). The existing water wells yielded about 27,000 m^3 of water per day. Water salinity shows high variability from west to east. It varies between 600 ppm along the northeastern sand dune zone and more than 6000 ppm along the northwestern coastal zone. Water composition varies between Na/Ca–HCO_3 along the fresh water zone to Na-Cl facies along the salty water zone reflecting interferences of seawater intrusion.

Rainfall along the Red Sea coast is less than 100 mm/year. However, thunderstorms of high precipitation rates could form intermittent flash floods causing catastrophic problems. Harvesting flood water could increase the recharge of groundwater resources of the coastal aquifer. Basins of Wadi Hodeen and Kerafon at the Red Sea coast have high groundwater potential as they have fair water quality (1000–1500 ppm). In the Ras Banas—Halayib Sector, where water is found in Quaternary sediments along the coastal zone's limited coastal strip, groundwater is the main source of fresh water. The salinity range for groundwater in these areas is between 1700 and 3400 ppm.

8 Conclusions

The construction of the Grand Ethiopian Renaissance Dam (GERD) on the upstream sections of the Blue Nile is expected to cause a significant water scarcity in Egypt. Great water demands due to increasing population rate and fixing water resource budget along with great water losses due to evaporation, damming of water flow, and supply are expected. As a result, it is advised that Egypt design a potential strategic plan for growing water resources that is based on developing traditional and non-traditional water resource supplies. The Nile water resources, which total 55.5 billion m^3 per year, are a significant supply of water in Egypt. Additionally, rainfall, flooding, and deep groundwater are scarce in the Sinai Peninsula, Western Desert, and Eastern Desert. Desalination is a water resource that can be explored and used, particularly in coastal areas that stretch east and north, as well as in some high-water salinity aquifers. The strategy also indicates that the agriculture sector uses 85%, industry 9.5%, and drinking 5.5% of the water supply. The plan gives Egypt's major groundwater reservoirs great attention as an alternative solution for water shortages for expanding agricultural and economic activities until 2030.

The major groundwater reservoirs of Egypt consist of several aquifers, summarized as: (1) The Nile Valley and Delta Aquifers, which are acknowledged as Egypt's main source of groundwater supplies, are among the most prominent of the many aquifers that make up the country's main groundwater reserves. It has a thick layer of sand and gravel on top of which is a clay cap that ranges in depth from 1 to 50 meters. 85% of Egypt's total groundwater abstractions are provided by it; (2) The Nubian Sandstone Aquifer System (NSAS) is Africa's most extensive fossil aquifer system, with reserves estimated at 150.000 Bm^3. Around 2.2 million km^2 of the NSAS are shared by Egypt, Libya, Sudan, and Chad, with Egypt contributing 828,000 km^2 (38%). With a hydraulic head that varies from 570 m above sea level west of Darfur to 78 m below sea level in the Qattara Depression, the NSAS has a maximum depth of 4500 m. From 200 m in East Uweinat to 3500 m northwest of El-Farafra Oasis, the fresh layer's thickness varies. Recent research has shown that the NSAS receives local recharge through significant fractures and joints along its southern outcrops as well as transboundary recharge from Egypt's, Sudan's, and Chad's southern and southwestern borders; (3) The Fissured Carbonate Rock Aquifer stretches from Sinai to Libya and makes up more than half of Egypt's land area. It serves as a confining cap to the Nubian Sandstone Aquifer System and features several natural springs. Recharge potential of the aquifer remains uncertain . (4) The Fissured Hard Rock Aquifer is commonly recharged by moderate quantities of infiltrating precipitation along the Eastern Desert and the Southern Sinai Peninsula. (5) The Moghra aquifer is located southwest of the Nile Delta, and groundwater is diverted into the Qattara Depression. It is replenished by rainfall and Nile aquifer recharge. (6) The Coastal Aquifer is recharged by local precipitation, and the abstraction rates are limited avoid saltwater upconing and seawater intrusion. The total reserved storage of the significant groundwater reservoirs of Egypt is expected to have a round figure of 1200 Bm^3 of variable recharge rates from high along the Nile Delta and Valley, moderate along the Coastal aquifer system to low along the Moghra Aquifer, and very low to non-renewable along the main Nubian Sandstone Aquifer m^3.

As water levels decrease across the majority of the Western and Eastern Deserts, as well as Sinai, the quality and sustainability of groundwater are in jeopardy. Over-pumping in the Nile Delta and in the Valley and El-Moghra aquifer areas to the west of the Nile Delta negatively impacts water quality by causing salinization and nitrate pollution. Therefore, the strategic approach should take these risk priorities into account. The hydraulic head decreases by around 0.5 m/y in arid conditions. For the long-term extension of these aquifers, recovery actions including reducing the number of pumping wells, cutting start-up and running periods, and switching to drip irrigation are crucial. It is highly advised to keep track on the quantity and quality of groundwater. On the other hand, careful extraction rates should be used and monitored in conjunction with the Nile Delta and Coastal regions, which are very sensitive aquifers, to minimize saltwater intrusion and deterioration of water quality.

The deep groundwater beneath the vast deserts of the western, eastern, and Sinai Peninsula along with limited quantities of rainwater and flooding are considered non-renewable resources and can be exploited according to the development conditions and the water needs. Non-traditional water resources, such as the reuse of exhaust uses from agriculture, industry, sanitary, and industrial effluent, are strongly suggested to meet Egypt's anticipated shortfalls in available water resources in the next years.

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